FORECASTING RESEARCH DIVISION

Technical Report No. 57

PROJECT DEFINITION STUDY OF ICING ATMOSPHERE FOR AIRCRAFT DESIGN

by

R W Lunnon

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Forecasting Research Division
Meteorological Office
London Road
Bracknell
Berkshire RG12 2SZ
United Kingdom

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Project definition study of icing atmosphere for aircraft design

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Chapter 1. Introduction

The European Joint Airworthiness Authorities (JAA) Research Committee has identified a number of aviation safety research items that have been submitted to the European Commission for funding. One of these was a major review of the current icing atmosphere used by the JAA (JAR25 Appendix C) to determine whether it should be amended taking account of new data recovery methods now commonly employed. Before such a major study could take place, a scoping exercise was considered necessary. This report presents this exercise and is aimed to define a programme which would benefit the aircraft certification authorities in establishing new design requirements and the air traffic services in having a better understanding of the probability and nature of atmospheric icing conditions encountered by aircraft in operation.

The existing icing atmosphere was derived almost exclusively by reference to in flight measurements of temperature, liquid water content (LWC) and, where possible, dropsize distribution. These measurements were made mostly in the late 1940s when they were almost the only available data. Although this design icing atmosphere has served the aviation community fairly well, it is known to have deficiencies in certain areas. More recently, other sources of data have become available, in particular remotely sensed sources (i.e. satellite and radar) and numerically simulated data. Chapter 2 of this report is an assessment of the current atmospheric definitions, including areas not covered, for example, freezing rain.

For aircraft design, small but quantifiable probabilities of failure of individual aircraft components are accepted. By analogy, some LWC values which have a small but quantifiable probability of occurring can lie outside the current icing design atmosphere. The problem is that large numbers of observations are required to determine the LWC values that have these very low probabilities of occurring: 10^{10} samples may be required to adequately define the atmosphere. Here, if one disregards the problem of specifying the dropsize information, and considers only a single horizontal and vertical integration scale (see below), then a sample is a single data point defining the temperature and LWC on the

scale of interest.

Obtaining this volume of data from remote sensing sources or by numerical simulation is perfectly practical. Furthermore, from satellites and numerically simulated data there is the potential for obtaining global or near global coverage for all seasons. The in flight measurements used in the past have very limited coverage in a global context. Another limitation of in flight observations is that when the safety of the experimental aircraft is threatened, evasive action must be taken which jeopardizes the generality of the measurements.

The proposed techniques will also be assessed to see whether they could be used to establish the probabilities of aircraft operating at different flight levels encountering icing conditions. Chapter 3 of this report is an overview of available data sources, with emphasis on whether enough data are available for a probabilistic definition to be feasible.

With a probabilistic design atmosphere specified, the thresholds for issuing forecast or nowcast warnings of dangerous icing conditions could be determined by the probability of the forecast event. For example, if public transport aircraft were designed to withstand icing events with a particular probability, if the forecast system was predicting an event with a lower probability, then a warning could be given. To allow for forecast error, a warning could be given if the forecast event had a slightly *greater* probability than the design requirement. By relating the threshold to the characteristics of the aircraft, a more relevant warning could be given, such that some aircrew would be better able to revise their flight plan. Of course all this would only be possible if the techniques used to derive the design icing atmosphere could be applied to data acquired in real time.

An enhanced ability to nowcast icing occurrences would also be of considerable value to the problem of aircraft 4-dimensional trajectory prediction. The use of anti-icing devices significantly affects the power requirements of the aircraft, thus changing its airspeed.

Chapter 4 of this report is a proposed work programme, specifying a number of work packages which would need to be completed before the new icing atmosphere could be generated. Options are given in this chapter, together with a rough order-of magnitude manpower requirements. For each work package there is an appendix describing in some technical detail what is required. Another appendix gives a list of contacts.

Chapter 2.

Assessment of current and future environment definition: range of:

(a) temperature,

(b) cloud condensate amount,

(c) hydrometeor size,

(d) horizontal integration scale,

(e) vertical integration scale,

(f) phase.

For most of the relevant parameters, the ranges addressed by the current civil design atmosphere (FAR25/JAR25), and the ranges in the proposed new environment are given in table 1. Other concepts which arise are vertical integration scale and phase. In the following sections the rationale behind the specification of the range is given.

Table 1.

Shows range of parameters in FAR25/JAR25 and proposed environment

	FAR25/JAR25	Proposed
Temperature	0°C - -30°C	5°C - -55°C
LWC (gm^{-3})	0.05 - 2.9	0.03 - 2.9
Hydrometeor size*	15μ - 50μ	1.6μ - 5mm
Horizontal integration scale	5km - 32km	5km - 1500km

*Note that in the FAR25/JAR25 definition the dropsizes are *mean effective dropsizes*, so effectively the definition addresses dropsizes both smaller than 15μ and larger than 50μ.

(a) Temperature

Clearly the warmest temperature to be considered will be close to 0°C. Indeed the warm limit for civil design atmospheres (FAR25, JAR25) is exactly 0°C. Icing will occur when the temperature of the collecting surface is below freezing, and commonly, in the absence of artificial heating, the collecting surface will have a temperature quite close to

that of the impinging air. Generally speaking, kinetic heating will raise the temperature of any surface, by an amount $\frac{rV_o^2}{2C_p}$, where V_o is the speed of the undisturbed flow relative to the collecting surface, C_p is the specific heat of air at constant pressure and r is the recovery factor, which is dimensionless, of which a typical value is 0.87 (see Jones, (1961) for a discussion of this). For a transport aircraft flying at 500 knots the kinetic heating is equivalent to a temperature rise of over 28°C, but other mechanisms will act to reduce this effect. Because the design atmosphere will have to be applicable to aircraft in all phases of flight, and with a large variety of cruise speeds, it is clear that in defining the warm limit of the temperature range, kinetic heating effects should be ignored.

There is a case for setting the warm limit to be above zero. Indeed, in the British military design atmosphere, defined by DEF STAN 00-970 leaflet 712/2, the warm limit is +5°C. The justification for a value above zero is twofold

(i) The problem of adiabatic cooling of air as, for example in the engine air intake - the induction system icing problem. This is undeniably a serious problem, as described by AIC 59/1990, and can occur at temperatures as high as 37°C. However, the problem is dominated by the effects of the vapour phase, and therefore consideration as to whether this should be included in the design atmosphere specification will be discussed in section (e) of this chapter.

(ii) The problem of an aircraft moving relatively rapidly from cold air to warm, moist air, e.g. on descent, and parts of the aircraft remaining at temperatures well below 0°C. Again this is a serious problem, although the parts of the aircraft most at risk, i.e. those nearest the fuel tanks (because the heat capacity of the fuel will mean that those parts warm up the slowest) are not critical to the control of the aircraft. However, having considered these issues, it was decided to set the warm limit to +5°C.

The issue of the cold limit is more complex. Ice clouds can exist at any sub-zero temperature so the issue of whether the ice phase is to be considered (to be addressed in section (e)) is clearly relevant. As far as the liquid phase is concerned, the civil design atmospheres go down

to a temperature of -30°C, with a possible extension to -40°C. However, it is documented that icing occurences have occured at temperatures down to -52°C, and clearly there is a strong case for allowing for this in the putative design atmosphere. A cold limit for the liquid phase of -55°C is tentatively suggested. For the ice phase, the DEF STAN 00-970 limit is -80°C. While clouds may exist at colder temperatures, there seems little reason for believing that the ice water content (IWC) probability distribution will be significantly different at the lower temperatures. Furthermore, the amount of heat required to vapourise ice in a saturated atmosphere at -80°C is not greatly different from that at -90°C. Therefore a cold limit for the ice phase will be taken as -80°C.

(b) Cloud condensate amount

If only the liquid phase is being considered, this equates to liquid water content (LWC). It has been agreed that what should be specified in the design atmosphere is not LWC but horizontally integrated LWCs (ILWCs) either for specified horizontal integration distances or giving rise to specified values of ILWC. Thus the limits of LWC may not be a major issue, but they are worth discussing. For example, in the pre-processing, volumes of air having LWCs below some threshold will be treated as cloud free and not subjected to further processing: clearly this threshold will have to be set so that correct ILWCs can be determined. Significant figures here are a flight sector length of 2500km, which is the maximum diversion which can be flown by a 180minute certified EROPS operation, and an ILWC of 7.5 gcm^{-2}, which if it all accreted to a surface would give rise to a an accumulation of ice 7.5 cm or 3" thick. These figures give an LWC of 0.03gm^{-3}, which is a useful minimum value to consider.

The maximum LWC which should be addressed can be gauged from current the literature.Zaitsev (1953) has apparently found an LWC of 2.24 gm^{-3} so this would be a useful indicator. However, given that the existing atmospheres cope with LWCs of 2.9 gm^{-3}, this has been taken as the upper limit.

Inevitably, using either remotely sensed or numerically simulated data, the concept of a gridsize will arise, and clearly the maximum gridscale LWC that will be found will be less than that that can occur on smaller

scales within the box. Therefore in processing the gridded data, the maximum to be found in that data will have to be considered.

(c) Hydrometeor size

In current civil design atmospheres, the problem of freezing rain/drizzle has generally been ignored so only cloud droplets (mean effective droplet diameter ranging from 15μ to 50μ) have been addressed. There is no doubt that freezing rain is a serious threat to aviation (see Mills Hicks & Mansfield, 1990, and Ahmed et al, 1993) so the future design atmosphere must allow for sizes of droplet up to and including raindrops. Raindrops exceeding about 5mm in diameter become unstable when falling, so this is a useful upper cutoff.

The problem of deciding the lowest dropsize that should be considered is more difficult. Collection efficiency depends on precise details of aerofoil shape and also on a trajectory similarity parameter K which in principle allows a single formula to be used for a range of different dropsizes, aerofoil sizes and airspeeds. A formula for K due originally to Bragg but quoted in FAA (1991) is

$$K = \frac{1}{18}\left(\frac{\rho_w^3 \, \delta^5 \, U^2}{c^3 \, \mu_a^2 \, \rho_a} \right)^{\frac{1}{3}}$$

where ρ_w is the density of water, δ is the dropsize, U is the airspeed, c is the characteristic length of the aerofoil, μ_a is the viscocity of air and ρ_a is the density of air. [Note. In FAA (1991) the square of U is omitted, but without it the formula is dimensionally incorrect and reference to Bragg et al (1981) implies strongly that U should be squared.] In deriving this formula Bragg makes use of an assumption about the drag on a droplet that may not be true at very high Reynolds numbers. High Reynolds numbers pertain for large droplets and high airspeeds. Nevertheless it is convenient to use a single formula to specify the collection efficiency as a function of all the variables on which it depends.

The dependency of the collection efficiency E on K is such that as K decreases E decreases assymptotically to zero, and as K increases, E increases asymptotically to one. However, for a range of values of K, E increases approximately linearly with log (K), and in determining the limiting values of dropsize we will extrapolate the linear part of the curve till the values of 0 and 1 for E are obtained. This gives limiting values of K of approximately 0.01 and 1.0.

In order to generate a value of δ such that droplets below this size can be ignored, we have to consider the largest value of U and the smallest value of c that are relevant. A typical cruising speed of a subsonic transport aircraft is 500 knots: supersonic aircraft are unlikely to be flying supersonically in the troposphere and there is little likelihood of stratospheric clouds causing a significant icing problem (see footnote to this chapter for a brief discussion of polar stratospheric clouds). The argument for sphere of radius 3" as the smallest sized object of relevance is more subtle. Generally speaking, discussion concers the question of how much LWC is required to give an ice accumulation of 3", on the inferred grounds that smaller amounts of ice will not cause a problem, except possibly on control surfaces. A small protuberence from the side of an aircraft, for example a pitot-head, may collect ice, even from a cloud containing only very small droplets, and its effective size may grow as a consequence, eventually to a size of 3". Once it has reached this size it should, in principle, act as a larger diameter collector. It follows from this discussion that the collection properties of objects having radii of less than 3" can in a sense be ignored. To obtain a K of 0.01 from an airspeed of 500 knots and a c of 3" requires a droplet size of 1.6μ. Thus droplets below this size will be ignored.

At the other end of the spectrum, to obtain a K of 1.0 from an airspeed of 100 knots and a c of 10 feet requires a droplet size of 454μ. What this tells us is that *all* droplets of size greater than 454μ will be collected, so it could be argued that discretising the dropsize information for dropsizes greater than this is unnecessary. However it

is recognised that the *effects* of large drops are not fully understood, but can be rather more than would be expected from consideration of collection efficiency alone (Cooper et al, 1984). Therefore, in anticipation that in the future the effects of large drops will become better understood, attempts will be made to provide dropsize information for all dropsizes up to the maximum theoretical raindrop size of 5mm. Note that a specific work package (WP2) will address the problem of defining naturally occuring dropsize distributions.

(d) Horizontal integration scales

In the FAR atmosphere, the standard distance for cumiliform clouds (i.e. the length scales for which the LWC values are defined) is 2.6nm. Shorter length scales are used in other atmospheres, e.g. IWCs for the UK civil design atmosphere are specified for lengths down to 1km. Two factors can be used to argue against the use of a minimum integration length of 1km or so. Firstly, the ILWC arising through such a short distance will be small: for example, an LWC of 2.24 gm^{-3} (the presumed maximum) integrated across 1km gives an ILWC of 0.22 gcm^{-2}, which if it all accreted would give rise to an accumulation of 0.22 cm, which is most unlikely to cause a problem. Secondly, meteorological observing systems and numerical simulation models have limited horizontal resolution (see chapter 2). Therefore a minimum integration length below 2.6nm will not be considered: the computational costs of working with a small minimum integration length may mean that a larger value is used. For example, an LWC of 2.24 gm^{-3} integrated across 33km gives an ILWC of 7.5 gcm^{-2} which is a significant threshold as discussed earlier.

As discussed earlier, a flight sector length of 2500km is the maximum diversion which can be flown by a 180minute certified EROPS operation, and this will be taken as the maximum horizontal integration length. Note that the existing civil design atmospheres do not consider horizontal integration scales longer than 17.4nm, which is clearly totally inadequate for assessing the effects of relatively low LWCs pertaining over long flight paths.

(e) Vertical integration scale

Just as the range of horizontal integration scales was addressed in section (d), it is appropriate to consider the range of vertical integration scales, although for rather different reasons. If it is assumed that the vertically integrated LWC (VILWC) through the depth of the cloud is to some extent constrained, i.e. clouds can be either thin with high LWCs or thick with low LWCs, then clearly there is scope for the design atmosphere providing information as to the extent to which this happens. For example, if the highest LWCs occur in clouds only 1000 feet thick, then the worst scenarios can be avoided by having the aircraft increase its altitude by one thousand feet or so. The figure of 1000 feet is significant here because it is the normal minimum vertical separation of aircraft, and therefore level changes generally occur in increments of 1000 feet. For that reasoning, the minimum vertical integration scale to be used will be 1000 feet. Note that the use of this figure does not imply that future aircraft will be designed in such a way that they will be **required** to change altitude when they encounter the severest icing: its use merely implies that the designer and regulatory authority can explicitly calculate the risks associated with any design which can only cope with finite localised LWC values.

The maximum vertical integration scale should be the maximum depth through which there could be an icing problem. This can best be evaluated by considering the range of temperatures, which is addressed in section (a).

One portion of the atmosphere of particular interest is the uppermost layer of any cloud, say the uppermost 1000 feet, for three reasons:

(i) LWCs are often at their highest here, and temperatures lowest (compared to lower in the same cloud).

(ii) The scope for a local vertical diversion to cloud free air is greatest here

(iii) This part of the cloud is best observed by satellite.

Given these factors, consideration will be given to generating statistics relating to the uppermost 1000 feet of cloud **separately** from the other statistics.

(f) Phase

Although the vapour phase can cause induction system icing, its statistical distribution will not be considered in the proposed study, for the following reason. The maximum specific humidity is, at a particular temperature, limited by the saturation specific humidity. Therefore the problem of ascertaining the probabilistic distribution of saturation specific humidities is simply an exercise in manipulating upper-air temperature data. Clearly a heating element for an induction system should be designed to cope with saturated air at the appropriate range of temperatures.

While specifying the liquid phase in the design atmosphere is regarded as essential, specifying the ice phase is regarded only as desirable. Note that whereas FAR25 covers only the liquid phase, other design atmospheres (e.g. British military) cover the ice phase as well. There is no known evidence that the ice phase causes problems to airframes, but it is understood that it may be a problem to engines. Therefore in the later sections of this report, the two phases will be costed separately.

Chapter 2 footnote - polar stratospheric clouds

The existence of these clouds has only been known about for the last decade or so, and the implications for the icing of aircraft are not fully understood. Nevertheless, it can be said that:

(i) the cloud condensate amounts are very low, by comparison with tropospheric clouds

(ii) the particle sizes are very small

(iii) they are predominantly of the solid phase

(iv) they are by no means pure water substance - there are significant amounts of other chemicals, and this may affect the adhesion properties.

All these factors suggest that these clouds do not pose a threat, and certainly there have been no reports of icing experiences from the

research aircraft flying extensive missions in these clouds. Therefore for the time being they will be ignored.

Chapter 3. Assessment of currently available data sources, from point of view of establishing feasibility of a probabilistic definition

Before considering whether the various data sources can generate sufficient data for a probabilistic definition to be possible, it is worth considering which parameters are addressed. Table 2 does this in summary form. Subsequent sections of this chapter describe the data sources in more detail, in particular covering the data rates.

From the data rate point of view there is little doubt that a probabilistic definition for the globe treating all levels together is feasible. If regional environments *or* environments having limited height range are needed, then use must be made of local observing systems, e.g. radar, full resolution AVHRR, limited area version of Unified Model. The provision of an environment for a specified region *and* limited height range is more difficult and the feasibility would depend on the precise size of the region and height range required.

Table 2. Shows basic observation capabilities of the various systems

		Temperature	Cloud Condensate	Dropsize	Length	Phase
UM	Global	✓	✓	×	100km - ∞	1
	Limited Area	✓	✓	×	50km - 6600km	1
	Mesoscale	✓	✓	×	17km - 1500km	1
Cox model		✓	✓	2	0 - ∞	✓
Radar	Conventional	×	3	3	2km - 1000km	×
	Dual Polarisation	×	3	3	300m - 160km	✓
	Vertical Doppler	×	✓	✓	2km	×
Satellite	SSM/I	×	4	×	25km - ∞	5
	AVHRR	6	×	6	1km - ∞	6
	METEOSAT	7	7	x	5km -18000km	7
RTNEPH		x	8	x	50km - ∞	x

Notes.

1. A mixed phase precipitation scheme is being developed for the UM, which may well be available by 1994 onwards.
2. At present the Cox model discriminates between cloud liquid water content and rain liquid water content, with the conventional dropsize threshold to discriminate between the two forms. However it will be straightforward to change the threshold so that all dropsizes that cause icing are treated as rain, thereby providing proxy dropsize information.
3. Radar reflectivities, when from pure liquid phase condensate, are an increasing function of both liquid water content and mean dropsize. However, neither parameter can be determined uniquely from radar data alone.
4. SSM/I retrievals provide information on the vertically integrated cloud condensate amount.
5. SSM/I retrievals have limited capability to discriminate liquid and ice phases.
6. AVHRR data can throw light on temperatures, dropsizes and phase of cloud *at cloud top.* Accompanying instrumentation can give an indication of temperatures lower in the cloud.
7. METEOSAT is cited as an archetypal geostationary satellite. It can provide information on the temperature of cloud top, and because it is believed that relatively new clouds are more likely to contain supercooled water, some inference about phase is possible.
8. RTNEPH documents the existence and altitudes of clouds, but little else

Note that none of the above data sources were available in the 1940s when the observations upon which the current environment is predicated were made.

3.1 Unified Model(UM)

3.1.1 General description.

The unified forecast/climate model (Cullen, 1993) is run both operationally, to provide global and local area forecasts up to a few days ahead, and as a climate model to predict climate change, typically in the next century. This dual role gives the advantage that, on any day, the model provides a realistic simulation of the current state of the atmosphere, particularly in the densely observed parts of the northern hemisphere, and in the areas of the world which are more sparsely observed, the model can be expected to produce a reasonable simulation of the climatology. It should be borne in mind that it is climatology that we are seeking to study, where by climatology we mean not only the mean state of the atmosphere but the magnitude and frequency of departures from that mean.

Because of the above considerations, and because of the magnitude of the data handling task, the concept of syphoning off data from the UM within a day or two of the time at which the data pertain is extremely attractive. This approach we will call "near-real time data accumulation". Retrospective data accumulation is also possible, but might require dedicated runs of the UM. Data could also be collected from runs of the model several years into the future, but because of the unavailability of real observed contemporaneous data, this is not envisaged.

3.1.2 Volume of data available

In the following table we are considering the UM as run operationally. Note that the vertical distribution of levels in the operational versions is not ideal as defined in section 1.6. Also it may be impracticable to extract from the operational runs of the model the data that are required. Nevertheless the number of observations per day make it clear that to generate a probabilistic atmosphere, with probabilities as low as 10^{-9} or so is definately feasible. Clearly at least one years worth of simulations would have to be used to avoid seasonal bias. To generate a seasonal specification to the same probability level would require four times as much data (assuming there are four seasons per

year), which is clearly feasible although the study would last longer and cost more. Similarly, more data would be required to generate an altitude specific specification, depending on the vertical resolution required. Regional specifications, covering the N Atlantic and Europe (using the limited area model) or, at even higher spatial resolution, covering most of UK domestic airspace (using the mesoscale model). The operational version of the mesoscale model has higher horizontal resolution than the 33km figure mentioned in 1.4, there will be a capability for generating an altitude specific specification with not more than a year's worth of data.

	Global	Limited Area	Mesoscale
Grid points	288 * 217 = 62496	229 * 132 = 30228	92 * 92 = 8464
Relevant levels	11	11	19
Timestep	10 minutes	5 minutes	1.5 minutes
Simulations	12	8	2
Obs per day	10^9	10^9	$3 * 10^8$

3.1.3 Merits

The main merit is that the data from the UM are readily available, have global coverage, are relatively straightforward to calibrate/validate (at least for global and LAM versions).

3.1.4 Limitations

The main limitations are the inability to distinguish the phase of the cloud condensate and the lack of dropsize distribution. Rectifying the former is a relatively small and well defined piece of work, and the cost of running the UM with a mixed phase cloud scheme would not be significantly greater than the costs without. On the other hand, adding a representation of different dropsizes would be a significant research project and would add greatly to the costs of running the model. Therefore this is not considered a realistic option.

3.1.5 Calibration/validation/algorithm development

The best calibration data set for the global and limited area versions is the data collected in the CASP-II experiment at the behest of Boeing

and Airbus. This consists of some thirty flights off Newfoundland in winter 1992 where the flight plan was designed to maximise the chance of encountering icing conditions. The methodology of calibration would be as follows. The UM data for the grid boxes and times for which aircraft were flying would be collected, and a probabilistic design atmosphere generated from those data. The same thing would be done from the aircraft data themselves. Note that there would only be a relatively small number of data points involved: an aircraft flying at 150m/s would only fly through about 11 LALM grid boxes in an hour so the number of data points would be ~10^3. If the two distributions were significantly different then further tuning of the cloud physics routines would be needed.

The major algorithm development, as mentioned above, would be the provision of a mixed phase cloud scheme. It is considered that this would be less work than the calibration/validation exercise, and intimately linked to it.

3.2 Cox model

3.2.1 General description

The Cox model (Cox, 1988), which is two dimensional, does not predict the wind field: the latter must be prescribed for it. What it does predict are temperature and the concentrations of water substance in various forms - vapour, cloud liquid, rain, graupel, cloud ice and snow. Generally the model is run with a prescribed updraft until a quasi-steady state cloud forms, and the properties of that cloud are then diagnosed.

3.2.2 Volumes of data available.

This is limited by the computer time available to perform simulations. Given sufficient time, provision of probabilistic, regional, seasonal and altitude specific specifications is clearly possible.

3.2.3 Particular merits

This is a relatively simple model to run and therefore generating the specification from the simulated quantities will be particularly straightforward. It can be used to simulate clouds anywhere in the

world, given appropriate initial conditions, which would probably be taken from the UM.

3.2.4 Limitations

The model provides no dropsize information. See below.

3.2.5 Calibration/validation/algorithm development

Calibration and validation can be carried out using CASP-II data. As far as developing a representation of different dropsizes is concerned, probably the most efficient scheme is that of Clark and Hall (1983). Probably of the order of a man-years work would be required to fully develop this scheme and include it in the model.

3.3 Conventional terrestrial precipitation radar

3.3.1 General description

Many countries, particularly in Europe, have such radars (usually S-band or C-band) and they are in routine use (see Collier, 1991, for example). For other general advantages/disadvantages see below.

3.3.2 Volume of data available

12 scans per hour

4 elevations : 0.5°, 1.5°, 2.5° and 4°

2km resolution data produced out to range of 210km

Number of pixels per scan/elevation = $\pi * (210/2)^2 = 3 * 10^4$

Data per day = $3 * 10^7$ *(per radar)*

Number of radars will increase this number to 10^9 - 10^{10}.

Clearly, from the point of view of quantity of available data, there is scope for addressing all the requirements here.

3.3.3 Particular merits

Aircraft icing potential is an increasing function of both liquid water content and dropsize, and the reflectivity measured by precipitation radar is an increasing function of those two parameters, so the instrument is in a sense subsuming two problems together.

3.3.4 Limitations

The combination of LWC and dropsize measured by radar is not the exactly

appropriate one for icing. Droplets of 420μ, all of which would accrete to an aircraft, might go undetected by radar. Reflectivities can be seriously distorted by the presence of melting snow - the bright band - and this is clearly a problem at temperatures close to zero. The inability to discriminate phase is a limitation, as is lack of temperature information. This leads us to consider that conventional terrestrial precipitation radar could only be used in conjunction with in situ measurements to resolve the ambiguities in the reflectivities. Therefore the issues of calibration/validation/algorithm development will be dealt with in chapter 4.

3.4 Dual Polarisation Radar

3.4.1 General decription

Because the beams are polarised, certain microphysical properties of the precipitation can be diagnosed (Illingworth and Caylor (1991)).

3.4.2 Volumes of data available

Instrument generates 60 beams in 30 seconds, with 512 range gates
This gives approximately 10^3 observations per second, or $8 * 10^7$ per day

3.4.3 Merits

Compared to conventional radar, the major advantage is ability to discriminate phase.

3.4.4 Limitations

Limited ability to discriminate dropsize and LWC, no temperature discrimination.

3.4.5 Calibration/validation/algorithm development

The dual polarisation radar under consideration is at Chilbolton, Hampshire, so clearly calibration using CASP-II data is out of the question. The best type of exercise would be flights of the C-130 research aircraft (or similarly instrumented aircraft) through the beam of the radar. Such exercises have been carried out in the past, but not in conditions particularly conducive to aircraft icing.

3.5 Vertically pointing Doppler radar

3.5.1 General description

The doppler returns give the vertical velocity of the raindrops, and from this their dropsizes can be derived: see Gossard and Strauch (1990). Note that the radar at Chilbolton has been dopplerised and so can operate in this mode. The combination of Doppler and dual-polarisation is particularly advantageous.

3.5.2 Volume of data available

This will be similar to that of dual polarisation radar, although there would be rapidly repeated scans of the same volume of air, so the data would not be independent.

3.5.3 Merits

Compared to non-Dopplerised radar, dropsize information will be available, which in turn will lead to more accurate LWCs.

3.5.4 Limitations

Still no temperature data available, and distinctly limited volumetric coverage.

3.5.5 Calibration/validation/algorithm development

Similar to Dual polarisation radar

3.6 SSM/I (Special Sensor Microwave Imager)

3.6.1 General description

SSM/I is flown on US Defence Meteorological Satellite Program (DMSP) satellites which are in sun-synchronous polar orbit (and an analagous instrument will be flown on European satellites from about the year 2000). Thus the coverage is global, although at fixed solar times, which may mean there are sampling limitations in the tropics. Data are available within a day or two of observation time. For an overview of the likely algorithms to be used see, for example, Petty and Katsaros (1990).

3.6.2 Volume of data available

Resolution: 25km

Swath width: 1400km

Path length per day: 40000*14 =560000km

Observations per swath = 56

Observations per day = 1254400 $\cong 10^6$.

3.6.3 Merits

SSM/I provides a direct measurement which can be related to vertically integrated LWC. Coverage is global. The instrument has been flying for several years so that provided the data have been archived properly, global, regional and seasonal probabilistic definitions of vertically integrated LWC should be possible. Limited discrimination between liquid and ice phases is possible, although almost certainly not to the standard required to produce a design specification of the ice phase.

3.6.4 Limitations

No temperature information, no dropsize information, no vertical resolution. By itself, SSM/I is not sufficient to provide useful information. However, combined with other data sources, a specification can be generated that would satisfy most requirements.

3.6.5 Calibration/validation/algorithm development

Calibration/validation exercises are being carried out by Penn State University using CASP-II data. Given that SSM/I will almost certainly have to be used in conjunction with other data, the development requirement is in that area.

3.7 AVHRR (Advance Very High Resolution Radiometer)

3.7.1 General description

AVHRR is flown on NOAA Tiros-N series satellite, which are sun-synchronous polar orbiters (having different local times from the DMSP satellites). Swath width is wider than for SSM/I, although difficulties arise near the edges of swaths. Again a European equivalent will fly from about the year 2000, although in an orbit to complement that of the US satellite. Work of particular relevance to ice determination has been performed by Ackerman et al (1990).

3.7.2 Volumes of data available

Resolution: 1.1km

Effective Swath width: 2252.8 (2048 points per line)

Distance traversed by satellite per day: 40000*14 =560000km

Observations per swath = 2048

Observations per day $\cong 10^9$ (per satellite)

Archived globally: 1 in 16 sample of the above = $6 * 10^7$

Available through Lasham [local satellite data reception station capable of receiving data covering Europe]:

(Assume one 50° of latitude pass and two 40° passes per 12 hours), so distance traversed by satellite per day while within reception range of Lasham = 260 * 111 = 28860

= 0.05 * global distance traversed by satellite per day

Hence observations per day through Lasham = $5 * 10^7$

3.7.3 Particular merits

Some information is available concerning temperature, dropsizes and phase of cloud at cloud top. Frequently the greatest LWCs occur near cloud top, so this information is potentially rather valuable.

3.7.4 Limitations

No information as to LWC is available. Because of the limitations of vertical penetration, there is a representivity problem. If AVHRR data can be used in conjunction with other sources, these limitations can be obviated.

3.7.5 Calibration/validation/algorithm development

Clearly it is necessary to assess the vertical penetration, using in situ observations from dedicated instrumented aircraft flights. Comparison with SSM/I data where the satellites are collocated, i.e. in the polar regions, is clearly desirable.

3.8 METEOSAT (and other geostationary satellites)

3.8.1 General description

METEOSAT provides continuous imagery coverage of the field of view (within 81° great circle arc of the subsatellite point which is latitude 0°, longitude 0°) in infra-red and water vapour channels, and visible channels when lit. See ESA (1978) for further details.

3.8.2 Volume of data available

No of infra-red pixels per image = $4.5 * 10^6$

Observations per day = $2 * 10^8$

3.8.3 Merits

Compared with polar orbiters, there is no diurnal bias in the sampling. Thus the data could be used to assess the magnitude of any diurnal variation in icing probability. Furthermore, it is believed that icing is particularly likely in new clouds which could be identified from sequences of imagery. However, it is not clear how to use this approach quantitatively.

3.8.4 Limitations

Provides information on the existence of cloud and the cloud top temperature: no quantitative data on liquid water content or dropsize.

3.8.5 Calibration/validation/algorithm development

Assuming data are used to identify new clouds, then a study would have to be performed to relate icing severity, as determined from incidents or in situ measurements, to "newness".

3.9 RTNEPH

3.9.1 General description

RTNEPH (formerly 3DNEPH) is a U.S. Air Force product which provides total cloud cover, cloud amounts for 4 cloud layers, the heights of whose bases and tops are specified. It is generated 3 hourly and has spatial resolution of 25nm. See Fye (1978) for details.

3.9.2 Volume of data available

Grid points on globe = $2 * 10^5$

Observations per day = $2 * 10^7$

3.9.3 Merits

RTNEPH is a complete description of where clouds are. It is a composite product, generated from a number of basic sources, so little algorithm development is needed. Has been used by Curry and Liu (1992).

3.9.4 Limitations

Cloud base information may be suspect in areas where there are few surface observations (although cloud base is always a source of uncertainty). Because it is a composite product, using this in conjunction with other, more basic, sources of data may cause problems.

3.9.5 Calibration/validation/algorithm development

Very little needed.

Chapter 4. Work programme

Essentially the action plan comprises the work packages, the sequencing of which is given below and the detailed technical nature of which is given in the appendices.

Figure 4.1. Shows flow of data between work packages (WPs)

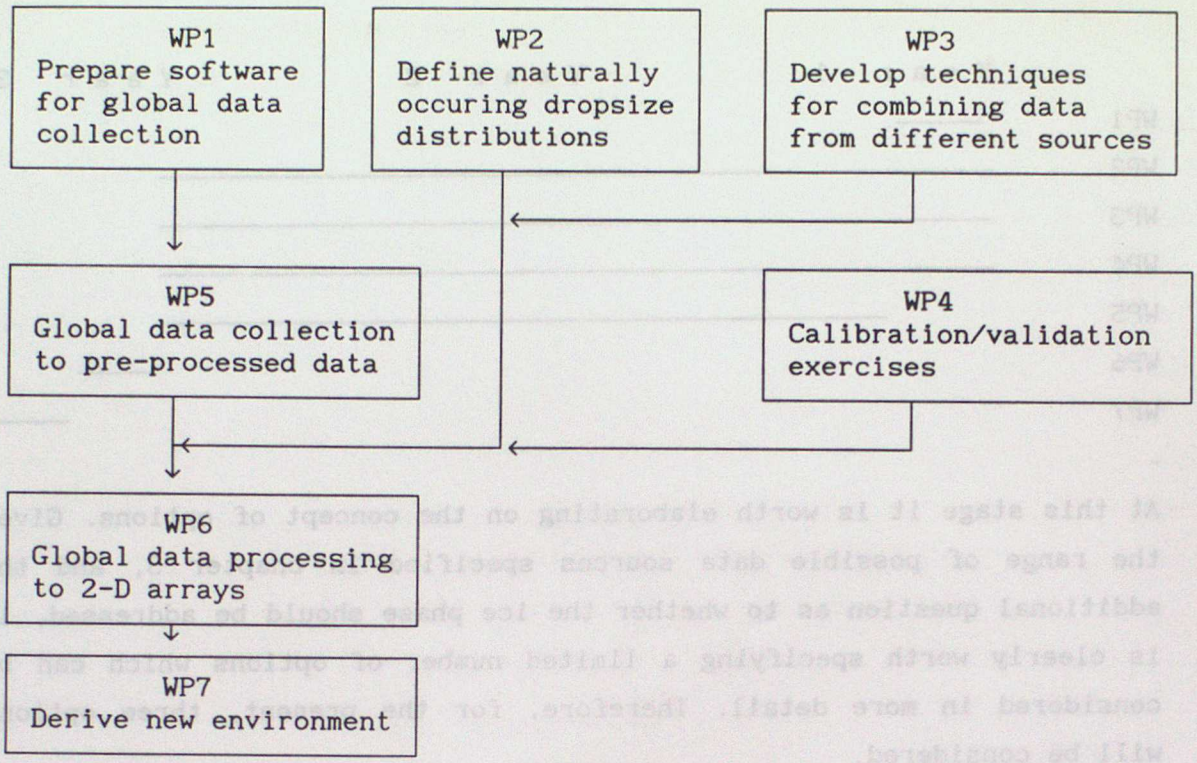
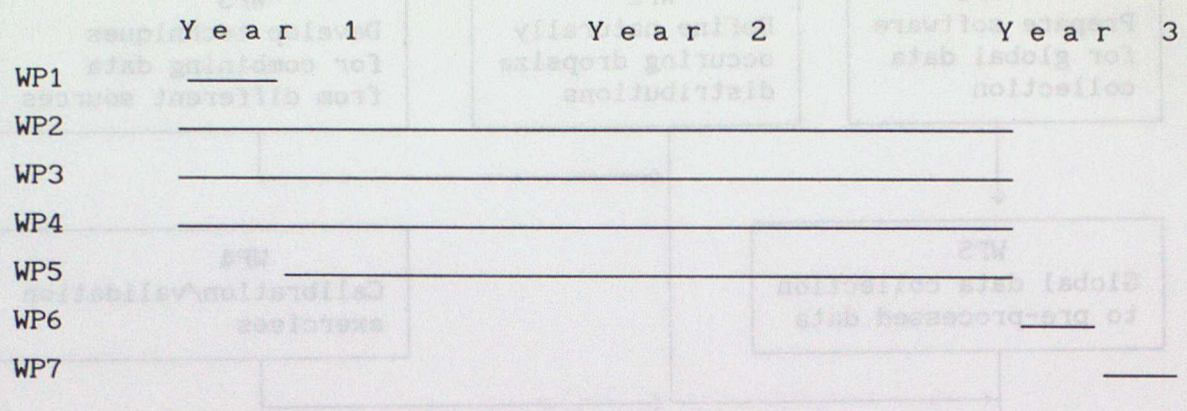


Figure 4.2 Shows progression of work packages for assumed 3-year programme



At this stage it is worth elaborating on the concept of options. Given the range of possible data sources specified in chapter 3, and the additional question as to whether the ice phase should be addressed, it is clearly worth specifying a limited number of options which can be considered in more detail. Therefore, for the present, three options will be considered.

Option 1 will make use of data from the Unified Model, the Cox model and SSM/I, and will not address the ice phase.

Option 2 will add the use of single-site, specialised radar (specifically the radar at Chilbolton, which has dual polarisation and doppler capability) and the use of AVHRR data, but will still not address the ice phase.

Option 3 will add the use of conventional precipitation radar, METEOSAT data, RTNEPH data, and will address the ice phase.

It is now possible to generate approximate manpower requirements for the individual work packages for the different options and these are given in table 4.2

Table 4.2.

Approximate manpower requirements for workpackages and options

(man-years)

	Option 1	Option 2	Option 3
WP1	.5	.7	1
WP2	.7	1	2
WP3	1	3	7
WP4	2	4	6
WP5	.5	.5	1
WP6	.5	1	2
WP7	.5	.5	.5
Project Management	.3	1.3	4.5
Total	6	12	24

It must be reiterated that these are approximate figures: what table 4.2 is intended to illustrate is that changing option has no effect on the cost of certain packages but a dramatic effect on the cost of others. For example, as one increases the number of data sources, the work to be done to combine the data (WP3) increases significantly: however the cost of the final computation does not change at all.

The work packages do not necessarily have to be conducted at a single institution, but, as hinted at in figure 4.1, there are advantages to having certain packages done in a single institution. Specifically, WPs 1,5,6,7 comprise the main number-crunching part of the work, and should ideally be done in a single location, but WPs 2,3 and 4 are more portable. Note that those latter WPs are the most labour intensive.

The rationale for option 1 is as follows. The data being considered fall into two basic categories: remotely sensed and numerically simulated. To use numerically simulated data with no constraint stemming from remotely sensed data would not be satisfactory: equally, no single remote sensing instrument can measure quantities from which **all** the icing parameters can be derived. Therefore it is proposed that a minimum configuration consists of a combination of remotely sensed data and numerically

simulated data. In order to obtain global coverage, the remote data must include some satellite data and some recourse must be made to a global numerical model, if only to provide boundary conditions for a higher resolution model. Therefore the minimum configuration which will be considered is SSM/I data, a version of the Unified Model and a high resolution numerical model, such as the Cox model. The latter would almost certainly be enhanced so as to provide dropsize information.

The weakness in the above is that the microphysical details are all obtained from models, with no reference to remotely sensed data. This weakness is ameliorated if two sources of remotely sensed data are added, which are those in option 2. The value of option 2 (as opposed to option 1) depends to a considerable extent on how important the dropsize information is. Because of the added data sources, option 2 is significantly more expensive than option 1, though. The enhanced diversity of observations used would add to the international credibility.

Option 3 essentially uses all observation sources, and in addition addresses the ice phase. Therefore clearly it will command the greatest international credibility, but the magnitude of the study means that there will be considerable overheads, as exemplified by the high project management costs. The value of the option depends to a considerable extent on the significance of the ice phase for aviation and it seems difficult to quantify this. It should be reiterated that the ice phase appears not to cause any airframe problems, merely problems through ingestion into engines, although with the exception of hail, it is difficult to see why the effects of ice cannot be quantified by simply multiplying the Ice Water Content by $(L_f + L_v)/L_v$, where L_f is the latent heat of fusion and L_v is the latent heat of vapourisation. If a more sophisticated formulation is required, dependent on ice crystal size, then almost certainly crystal habit will be a consideration in which case the problem assumes an extra dimension. Therefore the costings for option 3 should be regarded as even more approximate than the costings for the other options.

Appendix A1. Preparation of software for global data collection

Assuming option 1 as defined in chapter 4, the following is a reasonable way of proceeding. Clearly from UM fields, the first processing step would be the abstraction of data relating to SSM/I overpasses. The SSM/I and model data can then be combined, and those areas which are cloud free or the cloud top temperature is above 5°C (and there is no low level temperature inversion) eliminated from further consideration. Note that because it is necessary to generate statistics for long straight paths, it would be rational to partition the raw data into relatively simple geometric shapes, rather than following with great detail the isopleth that separates the cloud free and cloudy areas. Note also that low VILWCs would be interpreted as cloud free, if the inferred LWC in a layer of the specified incremental thickness (probably 1000 feet) was below the threshold (probably $0.03gm^{-3}$).

From the pre-processed data it should be possible to generate rather simply some sort of a climatology of where cloud is, in four dimensions. This should be compared with existing climatologies, e.g. Roach et al (1984), Rossow and Schiffer (1991), Stowe et al (1988, 1989) and Warren et al (1988).

Appendix A2. Define naturally occuring dropsize distributions

Complications arise from the facts that the proposed new environment
(a) is probabilistic
(b) addresses a large range of dropsizes, and
(c) has large horizontal integration distances.

If dropsizes are represented explicitly, then these three constraints imply that it is necessary to calculate covariances between the partial liquid water contents of *any number of* portions of the dropsize spectrum. For example, it could be supposed that a particular aircraft was prone to problems stemming from drops of size between, say, 15μ and 50μ, also to drops between 150μ and 500μ, and also drops between 1.5mm and 5mm. The design environment would have to say what were the probabilities of all permutations of partial liquid water content distributed between these parts of the spectrum, and do this for the appropriate range of horizontal integration scales. If the dropsize spectrum is discretised into N portions, then the number of statistics to be maintained for each horizontal integration scale would be approximately N!, which is considered to be unworkable.

One solution is the use of weighted mean liquid water contents, where the weighting is with respect to dropsize. However, implicit in the use of such an approach is the assumption that it is unnecessary to distinguish between droplet sizes above a certain size (that size being dependent on airspeed and component size). This is a somewhat unsatisfactory assumption, because in due course a better understanding of the way different dropsizes behave after impingement on the surface of the aircraft may emerge. Therefore the approach to be adopted is to study dropsize distributions and seek ways of representing them with a small number of parameters. Note that different ways of representing the dropsize information may be used in the generation of the 2-D arrays (WP6) and the derivation of the new environment - an explicit representation of the dropsize information is feasible at the 2-D array stage.

Many of the traditional dropsize distributions, e.g. Marshell-Parmer,

Langmuir-Blodgett, log-normal, assume that the distribution is monodispersed. However there is some evidence that bimodal size spectra exist - see, for example, Korolev (1991). However, it is interesting to note that, for a case in Japan, (Murakami et al, 1992) no supercooled cloud drops were found in a cloud, but a low concentration of drizzle drops coexisting with snow crystals. This suggests that the problem of representing dropsize spectra for a large range of dropsizes may be tractable and that, for example, the superimposition of two monodispersed distributions may be adequate.

In principle, the data collected in WP5 could be used to define the dropsize distributions. However, the techniques to be used to derive dropsize information from these data are not rigorously proven, and particularly if option 1 is adopted, there will be considerable uncertainty over the reliability of the derived information. Therefore it is recommended that in situ measurements are used for this aspect of the study. The cloud physics instrumentation on board the UK Met Office C-130, or other instrumented aircraft, for example the DLR research aircraft (Hoffmann and Roth (1989), Hoffmann et al (1990) can provide information on drops ranging from pratically the smallest cloud drop to the largest rain drop, and so is eminently suitable for this purpose. Note that we are not proposing to make extra measurements, merely analyse the existing data. A caveat has to be the reservations concerning the use of in situ measurements generally which were presented in the introduction. However, on balance it is considered that the advantages of using in situ data for this particualr application outweigh the disadvantages.

One problem remains that of discerning whether a parametric dropsize distribution representation represents the important properties of the explicit distribution correctly. It is considered essential that weighted mean liquid water contents (as defined below) are reproduced with negligible bias, and this will be one of the tests.

The definition of the weighted mean liquid water content is as follows. As discussed in chapter 2, for any characteristic size of aerofoil and airspeed, there will exist a droplet size threshold above which

practically all drops will adhere to the object. Thus it is possible to define a "weighting function" $W_{sv}(r)$, such that for an object of size c and airspeed u, the capture of water is determined by $\int W_{cU}(r)\ PLWC(r)\ dr$,

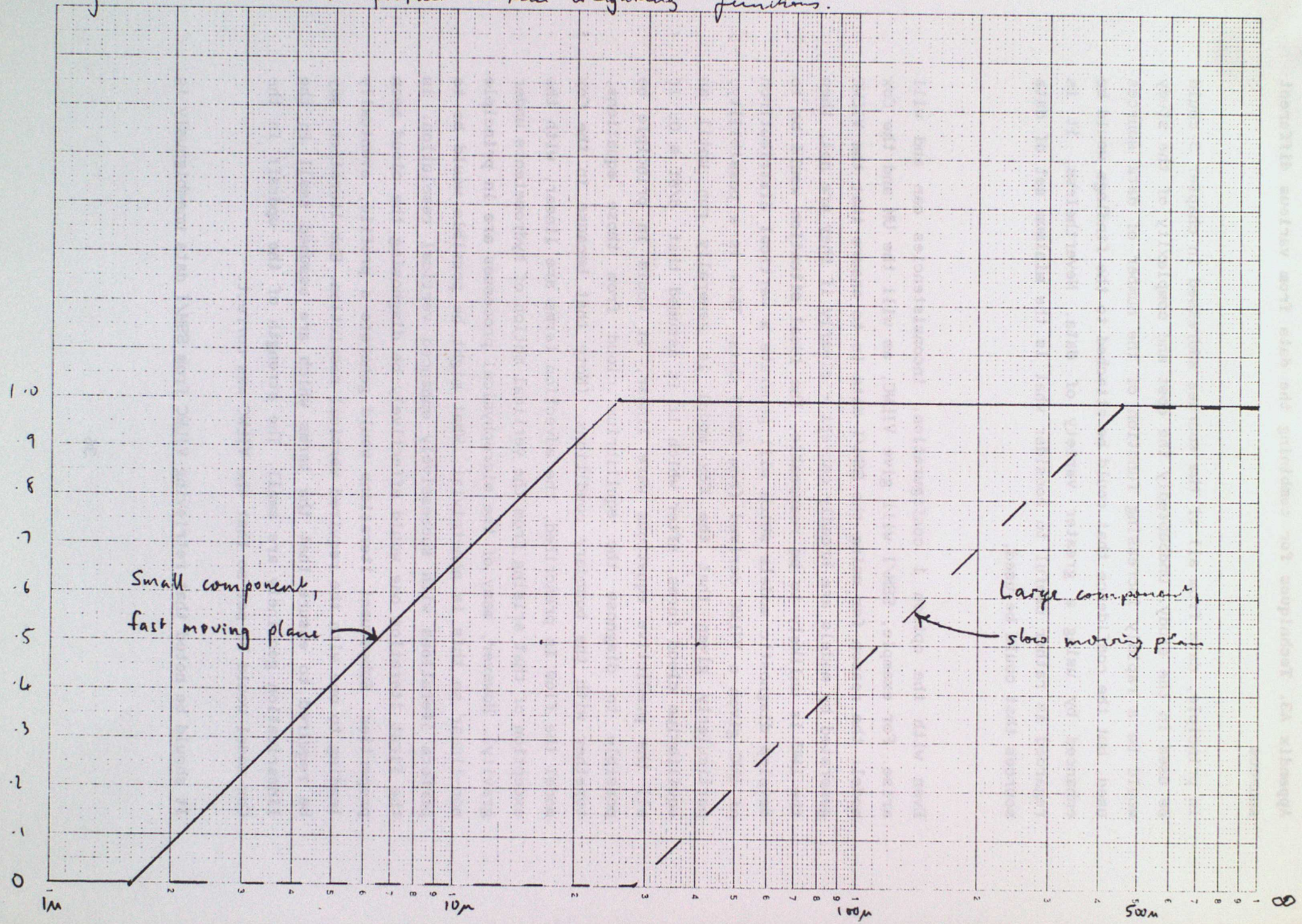
where $\int_{r1}^{r2} PLWC(r)\ dr$ is the LWC contained in drops having radii between r1 and r2. Hence $LWC = \int_{0}^{\infty} PLWC(r)\ dr$. In practice of course W_{cU} will be unity for most of the range of dropsizes (from at least 454μ, as noted in chapter 1) and for very small dropsizes it will be close to zero.

As in chapter 2 we will make the approximation that the portion of the curve where the collection efficiency is a linear function of log (K) can be extrapolated to values of collection efficiency of 0 and 1. The two extreme cases of the weighting function are shown in figure 1. For the continuous line the weighting function has a value of zero for dropsizes up to 1.6μ, the smallest size under consideration, and then increases such that it has the value unity for a dropsize of 25.6μ. For the dashed line, the weighting function is zero for dropsizes up to 28.4μ and then increases to the value of unity at a dropsize of 454μ, the size above which it is assumed all drops will accrete.

Figure A2.1 shows the envelope weighting functions: note that all that is required to define other weighting functions is a single dropsize δ at which the weighting function has the value 0.5, as the slope of the ramp in the weighting function is determined from equation (1). The figure suggests that those dropsizes should be uniformly distributed with respect to log(δ). In existing design atmospheres in which there is discretisation with respect to dropsize (e.g. UK military) the interval is 10μ. These last two considerations, together with the facts that δ for the two envelope weighting functions is 6.4μ and 112μ, suggest that there should be two intermediate weighting functions having δs of 16.5μ and 40μ. These vales of δ are indicated by dots on figure A2.1.

Graph Data Ref. 5531 Log 3 Cycles x mm, ½ and 1 cm

Figure A2.1 shows extreme proposed droplet weighting functions.



Appendix A3. Techniques for combining the data from various different sources

In principle, data from all of the sources addressed in chapter 3 could be used in the study. Undoubtedly the cost and complexity of the study would be a rapidly increasing function of the number of data sources used, but the confidence that could be attached to the findings would be enhanced by using a greater variety of data. Nevertheless, it is regarded as rather useful to consider what is the **minimum** set of data sources that could be used.

Even with the option 1 configuration, inconsistencies can and will arise. For example, SSM/I will give VILWC, as will the UM and the Cox model: the reason for using the SSM/I data is to ensure that the VILWC generated by models are broadly correct - clearly if they are not, then the LWC is unlikely to be reasonable. The ideal situation would be to develop diagnostic models which will generate a vertical distributiron of LWC given a VILWC derived from SSM/I data. This is a possibility, particularly given that the Cox model is generally run until an equilibrium cloud forms, after which it is assumed that $\partial/\partial t \cong 0$. If all the predictive equations were linear, it would in principle be possible to diagnose the equilibrium cloud from those equations, together with the boundary conditions. (Note that because in the Cox model the flow is prescribed, the advection terms are linear, with the exception of that arising from the vertical motion of hydrometeors under gravity). However, many of the microphysical processes are in principle non-linear so this is non-trivial. What might be possible would be to perform iterations with successively enhanced vertical resolution: in the first iteration one would effectively be diagnosing the cloud mean properties. Subsequent iterations would generate a profile, eventually leading to one with the required vertical resolution. Sub-iterations may be required to ensure that the terms which are assumed small in the linearisation genuinely are small. The strength of the updraft in the Cox model would be set so that the VILWC was correct.

It should be noted that retrieving VILWC from SSM/I data unambigously is

not straightforward. What has been done is using numerically simulated data to derive top-of-atmosphere radiances, e.g. Raustein et al (1991), Sand et al (1990). Clearly this kind of approach may be appropriate to this study.

In conclusion, the two-dimensional data set generated would be that resulting from the Cox model, but it would be such that the temperatures were essentially consistent with the Unified Model fields and the VILWC consistent with the SSM/I data.

Appendix A4. Calibration/validation/algorithm development

Assuming option 1 configuration of the Cox model, the UM and SSM/I data, it is essential to enhance the Cox model so that more explicit dropsize information can be provided. The method used by Hall (1980) appears to be appropriate, although note that it is not strictly necessary to simulate the number densities of a large number of size categories of ice particle. Thus the only extra complexity is accurate simulation of collision efficiency of interacting water drops. Hall used 69 different categories of dropsize, with radii ranging from 1 to 2580.3μ, wih the mass doubling every two categories. Using this approach, we would need 52 categories to cover the range from 1.6μ to 454μ. However, to cover larger droplets explicitly would only increase the computational requirements by some 30%, and given the uncertainties over the effects of large drops this is considered a worthwhile approach to follow. It may be possible to simulate the weighted mean LWCs directly, which would be more computationally efficient, and this should be investigated.

Generally speaking, the calibration/validation will consist of
(a) taking an observed data set, e.g. from the CASP-II experiment,
(b) averaging those data to the minimum scales specified in section 1,
(c) generating from the averaged in situ data all the statistics that would eventually be required,
(d) generating those statistics from the technique under consideration applied to the area and time in question
(e) comparing the statistics.

However, in order to understand what causes particular anomalies, it may be necessary for there to be comparisons between smaller data sets, e.g. a single flight compared with a particular simulation/remotely observed data set.

It should be emphasised that calibration/validation exercises should be performed in as wide a range of cloud conditions as possible. All cloud types should be sampled with the exception of cirrus (assuming it to be entirely ice-crystals, and assuming the study only addresses the liquid phase) and boundary layer cloud in temperate and tropical regimes.

Because of the role of aerosol on cloud formation, it is extremely desirable to have exercises performed both in continental air masses and maritime air masses. The availability of SSM/I data and the ease of rerunning historical cases will be factors in determining which field experiments are suitable for consideration.

Appendix A5. Global data collection to pre-processed data

This consists simply of running the software generated in WP1 on data, either in near-real time or retrospectively. In practice, almost certainly a combination of those two modes will be employed because clearly the new environment when it is produced should be based on recent data, but equally it is undesirable for an environment based on seven years worth of data to take seven years to assemble.

Appendix A6. Global data processing to 2-D arrays

This consists of the generation of a large number of two- or three-dimensional instantaneous datasets, in which the dimensions are spatial, in which the parameters represented are temperature, LWC and some representation of dropsize information.

The following would apply if the processing was based on the use of the enhanced (as described in appendix 4) Cox model, UM and SSM/I data. Given a scene selected by the pre-processing, the Cox model would be used to provide a detailed simulation, with boundary and initial conditions coming from the UM. The VILWC would then be compared with that from SSM/I after an equilibreum cloud had formed. The vertical motion field used in the Cox model would be adjusted to give the correct VILWC. The argument for this is that vertical motion in the UM, particularly on the grid scale, is one of the less reliable parameters (compared to say temperature and wind, which would be used in the Cox model). One of the challenges would be to identify scenarios of wind and temperature which were sufficiently different to justify simulation with the Cox model: clearly one could run the model with boundary conditions derived from every UM grid box, but this would be computationally prohibitive. Assuming the UM had a mixed phase cloud/precipitation scheme running, the LWC arising from the scheme could be used as a parameter to assess the usefulness of performing a simulation with the Cox model. If the UM is enhanced in this way, the only extra information to be obtained from the Cox model would be dropsize information, although the UM as run operationally does not have the required vertical and horizontal resolution.

Appendix A7. The derivation of the new design environment

This consists of the derivation of statistical quantities from the two- or three- dimensional arrays generated in WP6. Note that the generation of the statistical quantities can be performed sequentially, i.e. statistics from one array can be generated and added to the overall statistics before the second array is accessed. Thus although WP6 and WP7 are notionally separate scientific processes, they would almost certainly be performed as part of a single computational process, as the two-dimensional arrays will be rather large and therefore difficult to store.

The final product is a very large data base which would be made available to those wishing to demonstrate compliance of their equipment with the design standards. For a specific area and height range, and for specified vertical integration scale (probably 1000 feet), horizontal integration scale and weighting function of dropsize distribution, a probability distribution would be defined for combinations of weighted LWC and temperature.

Note that the same data in the two- or three-dimensional arrays would be used several times for different statistics.

One of the design considerations for this step is the required discretisation of the basic parameters, and this is discussed below.

(a) Temperature

In the FAR design envelope, the limiting values are specified at temperatures of 0°C, -10°C, -20°C and -30°C, with a possible extension to -40°C. Thus the discretisation is 10°C. With the exception of values at +5°C in the British Military design atmosphere, there appears to be no attempt to discretise finer than 10°C. Therefore this will be taken to be the required discretisation except between +5°C and -10°C, where the discretisation will be 5°C. There is a case for having increments of temperature such that approximately equal numbers of icing occurences fall into each histogram "bin". Although this approach has

its attractions, it makes the computation significantly more complicated and indeed it can be argued that, if the end product is a probabilistic design atmosphere, then only at the end of the exercise will the distribution of the bins be known. However, this philosophy will be used to argue that, because icing occurences at temperatures below -40°C are rare, than a discretisation coarser than 10°C can be used at these very low temperatures. Thus, assuming that the lower temperature limit is -55°C, a single bin will be used for all occurences between -40°C and -55°C. Indeed, if a low temperature limit lower than -55°C is taken, the size of the last bin will be expanded to cope with it.

(b) Cloud condensate amount

Discretisation of cloud condensate amount is straightforward, given a clearly defined, finite, minimum value of $0.03gm^{-3}$. This should be taken as the discretisation.

(c) Dropsize information

This will have to await the outcome of WP2 which will define how the dropsize information is to be presented.

Appendix: European Contacts

The following responded positively to an appeal for those interested in involving themselves in this work

Institut für Physik der Atmosphäre
Herr Prof Schumann, NE-PA
Oberpfaffenhofen
82234 Weßling
Germany
Fax ++49-8153-281841
Tel ++49-8153-28521

Ing Giovanni Bertolone
Tecnologia del Velivolo
Divisione Velivole Difesa
C.SO MARCHE 41
10146 TORINO
Italy
Fax 011/7181078
Tel 011/7181878

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